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ELECTRO-OPTICAL GLAZING STRUCTURES ~~HAVING SCATTERING AND TRANSPARENT MODES OF OPERATION AND METHODS AND APPARATUS FOR MAKING THE SAME~~ AND LIQUID CRYSTAL MATERIALS FOR USE THEREWITH

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RELATED CASES

This is a Continuation-in-part of: copending Application No. 09/032,302 filed February 27, 1998, which is a Continuation-in-part of copending Application Serial No. 08/805,603 entitled "Electro-optical Glazing Structures Having Total-scattering And Transparent Modes Of Operation For Use In Dynamical Control Of Electromagnetic Radiation " filed February 26, 1997; copending Application Serial No. 08/739,467 entitled "Super Broadband Reflective Circularly Polarizing Material And Method Of Fabricating And Using Same In Diverse Applications", by Sadeg M. Faris and Le Li filed October 29, 1996, which is a Continuation-in-Part of copending Application Serial No. 08/550,022 entitled "Single Layer Reflective Super Broadband Circular Polarizer and Method of Fabrication Therefor" by Sadeg M. Faris and Le Li filed October 30, 1995; copending Application Serial No. O8/787,282 entitled "Cholesteric Liquid Crystal Inks" by Sadeg M. Faris filed January 24, 1997, which is a Continuation of Application Serial No. 08/265,949 filed June 2, 1994, which is a Divisional of Application Serial No. 07/798,881 entitled "Cholesteric Liquid Crystal Inks" by Sadeg M. Faris filed November 27, 1991, now US Patent No. 5,364,557; copending application Serial No. 08/715,314 entitled High-

Brightness Color Liquid Crystal Display Panel Employing Systemic Light Recycling And Methods And Apparatus For Manufacturing The Same" by Sadeg Faris filed September 16, 1996; and copending Application Serial No. 08/743,293 entitled "Liquid Crystal Film Structures With Phase-Retardation Surface Regions Formed Therein And Methods Of Fabricating The Same" by Sadeg Faris filed November 4, 1996; each said Application being commonly owned by Reveo, Inc, and incorporated herein by reference in its entirety.

BACKGROUND OF THE INVENTION

Field of Invention

The present invention relates generally to an electro-optical structures having total-scattering and semi-transparent and totally-transparent modes of operation which are electrically-switchable for use in dynamically controlling electromagnetic radiation flow in diverse applications, such as electro-optical glazing structures, and also to improved methods and apparatus for producing such electro-optical structures in a large-scale and uniform manner, without defects or haze required applications such as switchable privacy window glazings.

Brief Description of the Prior Art

The use of windows in homes, commercial buildings, and automotive vehicles alike is very well known. The reasons for providing windows in such structures and systems are directly related to the functions they perform. For example, window structures provide for ventilation, lighting, a sense of spaciousness, as well as a way of making contact with the outdoors. Windows

made of glazing (e.g. glass material) also permit selective transmission of electromagnetic radiation between the outdoors and the interior space of homes, commercial buildings, and automotive vehicles. While conventional forms of glazing serves many useful functions, such forms are not without problems.

An appreciation of the problems presented by the use of conventional glazing in windows, can be most easily attained by recognizing the nature and composition of electromagnetic radiation with which windows universally come in contact.

On a clear day at sea level, electromagnetic radiation is composed of 3% ultraviolet light (i.e. electromagnetic radiation in the UV band), 44% visible light (i.e. electromagnetic radiation in the visible band), and 53% infrared light (i.e. electromagnetic radiation in the IR band). In accordance with the laws of physics, 50% of all electromagnetic radiation produced is left hand circularly polarized (LHCP) while the other 50% thereof is right hand circularly polarized (RHCP). The total electromagnetic radiation striking a window surface is a combination of direct radiation from the Sun and diffuse radiation from the ambient environment. While electromagnetic radiation is broad-band in nature, it is the ultraviolet light component thereof which causes molecular decomposition in various types of plastic material and inorganic dyes, which results in color fading.

When electromagnetic radiation strikes a glass window, three different physical processes occur. Some of the radiant energy is transmitted through the glass; some of the radiant energy is reflected off the glass; and a small portion of the radiant energy is absorbed by the glass. The energy transmitted through the glass window is typically absorbed by furnishings or structures within the

interior environment, and often becomes trapped therewithin causing an increase in interior temperature.

Depending on the season, electromagnetic radiation transmitted through glass windows can be either mitigate or worsen the thermal loading imposed upon the heating and cooling systems associated with the glass windows. Consequently, during the hot weather season, it is highly desired to shield windows and sliding glass doors from electromagnetic radiation in order to lessen thermal loading upon cooling systems. During cold weather season, it is highly desired to expose windows and sliding glass doors to electromagnetic radiation in order to lessen thermal loading on heating systems.

In short, it is highly desired to selectively control the transmission of electromagnetic radiation through window structures at different times of the day and year so that thermal loading upon the heating and cooling systems of residential, commercial and industrial building environments can be minimized. By minimizing such thermal loading, power can be used in an economical manner to control the internal temperature of residential, commercial and industrial building environments. Achievement of this goal would impact the natural environment in a positive manner, while improving the quality of life.

With such objectives in mind, great effort has been expended in recent times to improve the ways and means of selectively controlling the transmission of electromagnetic radiation through window structures.

One approach to electromagnetic radiation control involves using a window shade to reduce the transmission of electromagnetic radiation through windows. The most popular type of shade is the window blind. However, as window blind is mounted within the

interior of the building or transportation environment, electromagnetic radiation is allowed transmit through the window, raise the temperature within the internal environment, and thus increase thermal loading on cooling systems during the hot weather season. Also, the operation of window blinds requires mechanical or electro-mechanical controls which tend to be bulky and expensive to manufacture, install and maintain.

Another approach to electromagnetic radiation control involves the use of sun control films which are physically applied to the surface of glass windows in building and automotive vehicles alike. Presently a variety of different types of sun control film are marketed by various firms. Such electromagnetic control films can be categorized into one of the three basic categories, namely: high reflectivity film; heat saving or winter film; and fade protection film.

High reflectivity electromagnetic films are most effective at blocking summer heat. The higher the reflectivity of electromagnetic film, the more effective it will be at blocking electromagnetic radiation. Electromagnetic reflectivity film having a silver, mirror-like surface is more effective in blocking electromagnetic radiation than the colored, more transparent films. Electromagnetic reflectivity films can lower the U-value of glass by more than 10%. Notably, in climates having long heating seasons, the use of high reflectivity film prevents using the winter sun to warm the interior of buildings during the cold weather season, and thus lessen thermal loading on building heating systems.

Heat-saving or winter films are designed to reduce winter heat losses through glazing. These films can lower the U-value of glass windows by more than 20%.

Fade-protection films are designed to filter out ultraviolet rays. Ultraviolet rays cause about 60-65% of color fading in most home furnishing fabrics and automobile dash boards.

While electromagnetic radiation control films of the types described above can be used to control heat and glare, eliminate sun damage, and to a lesser extent, reduce visibility into buildings during the daytime. The major disadvantages thereof are reduction in interior light, loss of visibility, and extra care required in cleaning. Moreover, prior art electromagnetic window films are incapable of changing from transmissive during winter months to reflective during summer months in order to effectively use electromagnetic radiation for dynamic temperature control of biological environments (e.g. human habitats, greenhouses and the like).

An alternative approach to electromagnetic radiation control involves using special glass panels having radiation transmission characteristics which effectively absorb (i.e. block) the infrared and ultra violet wavelengths, while transmitting the visible wavelengths thereby allowing window viewing and day light to enter the interior spaces of buildings using such window technology. While the light transmission characteristics of such glass provides a measure of electromagnetic radiation control during cooling seasons, where outdoor temperatures tend to be above 72 degrees Fahrenheit, its IR absorption characteristics prevents, during heating season, IR wavelengths of Sun light to warm the interior spaces of building structures in which such glass panels are installed. Consequently, during heating seasons, such glass fails to lessen the thermal loading on the heating systems of such buildings, as would be desired in an effort to conserve energy and heating resources during the winter months.

In recent times, there has been great interest in using variable light transmission glass or glazing, referred to as "*smart windows*", to achieve electromagnetic radiation (i.e. energy) control in buildings and vehicles alike. The reason for using smart window structures, rather than conventional glass window panels, is quite clear. Smart window structures have light transmission characteristics that can be electrically controlled during the course of the day (or year) in order to meet lighting needs, minimize thermal load on heating and/or cooling systems, and provide privacy within the interior spaces of buildings and vehicles alike.

The use of chromogenic switchable glazing or smart windows for controlling the flow of light and heat into and out of a glazing according to occupant comfort, is discussed in great detail in the following papers: "Chromogenic Switchable Glazing: Towards the Development of the Smart Window" by Carl Lempert published in the June 1995 Proceedings of the Window Innovation Conference, Toronto, Canada; and "Optical Switching Technology for Glazings" by Carl Lempert published in Thin Solid Films, Volume 236, 1993, pages 6-13, both incorporated herein by reference.

In general, there are several different types chromogenic switchable glazing or smart windows, namely: non-electrically activated switchable glazings; and electrically-activated switchable glazings. The non-electrically activated types of chromogenic switchable glazing are based on: photochromics, thermochromics and thermotropics. The most common electrically-activated types of chromogenic switchable glazing are based on polymer dispersed liquid crystals (PDLC), dispersed particle systems (DPS), and electrochromics.

Prior art smart window structures based upon conventional twisted nematic (TN) or super twist nematic (STN) liquid crystal

technology require the use of a pair of polarizers. This, however, results in high optical loss, as up to 60% of the incident light is absorbed by the polarizers, in the desired non-blocking mode of operation.

While a smart window structure based on polymer dispersed liquid crystal (PDLC) technology offers better performance than TN or STN based window structures, such smart window structures suffer from several significant shortcomings. Such electrochromic technologies are disclosed in greater detail in "Laminated electrochromic device for smart windows" by P. Schlotter, G. Baur, R. Schmidt, and U. Weinberg, P.351, Vol. 2255 (1994), and particle suspended technologies as disclosed in U.S. Patent 4,663,083, entitled "Electro-optical dipole suspension with reflective-absorptive-transmissive characteristics" issued to Alvin M. Marks.

For example, when a voltage is applied to the electrochromic device in its "clear" state, it darkens as ions (such as lithium ions) and associated electrons transfer from the counter electrode to the electrochromic electrode layer. The tinting continues until the electrochromic system reaches its most opaque state. Reversing the voltage polarity causes the ions and associated electrons to return to the counter electrode, and the device becomes more transparent. However, the electrochromic device suffers from slow response time and shorter life-time. In particle suspended technology, the micro-sized dipole metal flakes are suspended in a carrier. When no electric field is applied, the particles are more or less randomly oriented. Therefore, the light is mostly reflected and/or absorbed, resulting in a low transmittance. When an electric field is applied across the device thickness, all the particles are aligned in the field direction. The device shows an optically transparent state.

However, this technology has a problem associated with the settling of the metal particles due to gravity..

Using liquid crystal to make electrically controllable light devices has the promise to overcome these problems. These devices introduce a polymer matrix in liquid crystal materials that can be switched from translucent to transparent state by applying an electric field.

One known method of creating a switchable electro-optical device using stabilized liquid crystal structures is polymer dispersed liquid crystal (PDLC) technology as disclosed in "Polymer-Dispersed Liquid Crystals: Boojums at Work", by J. William Doane, in MRS Bulletin/January, 1991. PDLC technology involves phase separation of nematic liquid crystal from a homogeneous liquid crystal mixture containing a suitable amount of polymer. The phase separation can be realized by polymerization of the polymer. The phase separated nematic liquid crystal forms micro-sized droplets dispersed in the polymer bed. All synthetic resins proposed before this invention are of the isotropic phase with an index n_p matching the ordinary index n_o of the nematic. In the off state, the liquid crystal molecules inside the droplets are randomly oriented. The mismatching of the refractive indices between the polymer bed and liquid crystal droplets causes the device to exhibit a translucent state, i.e., a light scattering state. When an electric field is applied, the liquid crystal orients in such a way that $n_o = n_p$, resulting in a transparent state. The main disadvantage of the PDLC technology is the inherent haze caused by the optical index mismatching, particularly at large viewing angles.

The second problem associated with prior art PDLC technology is its high cost of manufacture. Virocon/3M (U.S.A.), and

Raychem/Taliq (U.S.A.) are commercial manufacturers of privacy window glazing based on PDLC technology. Due to the extremely high price of manufacture, such manufacturers are facing significant obstacles in expanding the PDLC privacy window market.

U.S. Patent 5,691,795 entitled "Polymer Stabilized Liquid Crystal Light Modulation Device and Material" by J. William Doane et al, incorporated herein by reference, discloses another liquid crystal technology based on liquid crystal polymer stabilized cholesteric texture (PSCT), which can be used to create electro-optical structures, such as electro-optical glazing structures. In PSCT technology, a small amount of UV cross-linkable polymer in its liquid crystal phase is mixed with cholesteric liquid crystal (CLC) whose pitch is tuned to the infrared region. The mixture is then cured by exposure to UV light while a voltage is applied to align the liquid crystal as well as the polymer molecules in the direction across the device thickness. After curing and when no electric field is applied, the liquid crystal material exists in a special cholesteric phase, i.e., a focal conic state. In this phase, the liquid crystal material exhibits a translucent state that is stabilized by the polymer network. When an electric field is applied, the CLC molecules are untwisted and aligned along the direction of the electric field, resulting in a transparent state. Since this technology requires much lower polymer concentration than that of PDLC technology and does not have liquid crystal droplets, it exhibits significantly lower haze, particularly when the refractive index of the polymer matches that of the cholesteric liquid crystal. However, this approach calls for polymerizable liquid crystalline material(s) to act as the polymer to stabilize the focal conic cholesteric phase.

Prior art PSCT technology has at least five significant problems which hitherto have neither been addressed or solved in a satisfactory manner.

First, PSCT technology imposes a high requirement on the selection of the polymer materials since liquid crystalline polymer that has a mesogenic group is needed as disclosed in U.S. Patent 5,691,795, supra. Such a liquid crystal polymer material needs to be specially synthesized. Therefore, the cost of such a liquid crystalline polymer becomes extremely high, making the price of the PSCT device even higher than that of the PDLC.

Secondly, in typical PSCT systems, since monomers with mesogenic groups are used, the formation of the polymer network will partially alter the orientational order at each cross-linking site. Due to the presence of the mesogenic groups on the polymer network, the non-reactive liquid crystal molecules that are close to the network are now strongly anchored onto the network. To switch all liquid crystal molecules along the direction of the applied electric field, a strong field is needed. Such a field often brings about electric shorting problems. To avoid shorting, a switching electric field of modest strength is adopted by industry. However, the liquid crystal molecules close to the polymer network will not respond to a modest switching field, resulting in strong haze, particularly at large oblique angles.

Thirdly, scaling-up the panel size of PSCT-based devices has been very difficult in practice. To make the device in large sizes, the same lamination technology adopted in making the PDLC can not be used because the glass substrates themselves are used to support the PSCT structure as the PSCT material is basically in a liquid-gel-like state.

Fourthly, making a large-size uniform PSCT device is difficult because this lamination method cannot be used. Rather, a filling method is called for. However, when filling liquid crystal into a large size panel, the flow streaks of the liquid crystal and polymer mixture induce readily noticeable marks. Therefore, the resulting PSCT device appears very non-uniform.

Finally, the cost of glass substrates with conductive Tin Oxide layer coatings is very expensive when using PSCT-based technology. Also, the cost of plastic substrates with conductive Tin Oxide layer coatings is very expensive when using PDLC technology. Such factors contribute to the high price of electro-optical devices based on PDLC and PSCT technologies.

Accordingly, there is a great need in the art to improved means and ways of manufacturing large-size liquid crystal based electro-optical glazing structures at lower costs than that afforded by prior art manufacturing systems and methodologies.

Thus it is clear that there is a great need in the art for an improved form of variable light transmission glazing structures and methods and apparatus for making the same in a way which avoids the shortcomings and drawbacks of prior art technologies.

OBJECTS AND SUMMARY OF THE PRESENT INVENTION

Accordingly, a primary object of the present invention is to provide an electro-optical glazing structure which avoids the shortcomings and drawbacks of prior art technologies.

Another object of the present invention is to provide an electro-optical glazing structure which has total-scattering and total-transmission modes of operation for improved control over the flow

of electromagnetic radiation within the solar region of the electromagnetic spectrum (i.e. Solar Spectrum).

A further object of the present invention is to provide such an electro-optical glazing structure, in which the modes of operation can be electrically-activated or switched, while avoiding the use of energy absorbing mechanisms.

A further object of the present invention is to provide such an electro-optical glazing structure having a broad band of operation, including the near-IR, visible and near-UV portions of the electromagnetic spectrum.

Another object of the present invention is to provide an actively-controlled window or viewing panel constructed from the electro-optical glazing structure of the present invention, wherein the transmission of electromagnetic radiation over the near-UV and near-IR regions of the electromagnetic spectrum can be totally scattered, rather than absorbed, reducing the temperature cycle range which the window structure is required to undergo.

Another object of the present invention is to provide a large-size actively-controlled window or viewing panel employing an electro-optical glazing structure fabricated from a polymer stabilized cholesteric texture (PSCT) that uses low cost liquid crystal materials.

Another object of the present invention is to provide a large-size low-cost electro-optical glazing structure having uniform optical characteristics and is constructed using low-cost PSCT polymer materials.

Another object of the present invention is to provide a PSCT-based electro-optical glazing structure that uses a polymer which does not have the liquid crystalline phase (i.e. the polymer does not

have the mesogenic group) as required by prior art liquid crystal compounds.

Another object of the present invention is to provide a PSCT-based electro-optical glazing structure that uses dichroic dyes in a low cost PSCT material.

Another object of the present invention is to provide a large-size PSCT-based electro-optical glazing structure that can be switched using relatively lower voltages than that required by prior art devices.

Another object of the present invention is to provide a PSCT-based electro-optical glazing structure that has improved mechanical strength.

Another object of the present invention is to provide a PSCT-based electro-optical glazing structure that uses low cost glass substrates.

Another object of the present invention is to provide a PSCT-based electro-optical glazing structure that uses low cost glass substrates with insulating layers.

Another object of the present invention is to provide a PSCT-based electro-optical glazing structure made using a special additive which eliminates liquid crystal flow streaks.

Another object of the present invention is to provide a PSCT-based electro-optical glazing structure which is made using a low cost conductive layer as electrode surfaces on the glass substrates thereof.

Another object of the present invention is to provide an improved method of fabricating a PSCT-based electro-optical glazing structure manufacture process in a way which enables the

manufacture of low-cost PSCT-based devices having surface areas greater than 2 meters x 3 meters.

Another object of the present invention is to provide an improved system and method for making low-cost PSCT-based electro-optical glazing structures which are haze-free, defect-free, and have uniform optical characteristics over the surface area of the device.

Another object of the present invention is to provide an improved system and method for making low-cost PSCT-based electro-optical glazing structures using inexpensive liquid crystal material which does not have the liquid crystalline phase (i.e. the polymer does not have the mesogenic group) as required by prior art liquid crystal compounds.

Another object of the present invention is to provide an improved system and method for making low-cost PSCT-based electro-optical glazing structures which utilizes float-glass fabrication techniques.

Another object of the present invention is to provide an improved system and method for making low-cost PSCT-based electro-optical glazing structures which involves the addition of a surfactant in order to achieve uniform optical properties across the entire surface of the electro-optical glazing structure.

Another object of the present invention is to provide an intelligent window system for installation within a house or office building, or aboard a transportation vehicle such as an airplane or automobile, wherein the electro-optical glazing structure of the present invention is supported within a prefabricated window frame, within which are mounted: a electromagnetic-sensor for sensing electromagnetic conditions in the outside environment; a

battery supply for providing electrical power; a electromagnetic-powered battery recharger for recharging the battery; electrical circuitry for producing glazing control voltages for driving the electrically-active elements of the electro-optical glazing supported within the window frame; and a micro-computer chip for controlling the operation of the battery recharger and electrical circuitry and the production of glazing control voltages as required by a radiation flow control program stored within the programmed microcontroller.

A further object of the present invention is to provide such an electro-optical window structure which is designed for integration within the heating/cooling system of a house, office building, factory or vehicle in order to control the flow of broad-band electromagnetic radiation through the electro-optical window structure, while minimizing thermal loading upon the heating/cooling system thereof.

Another object of the present invention is to provide a thermal/viewing shield or panel made from electro-optical glazing structure of the present invention.

Another object of the present invention is to provide of an intelligent pair of sunglasses, in which each optical element is realized using an electro-optical glazing structure of the present invention, fashioned to the dimensions of a sunglass frame.

Another object of the present invention is to provide of an intelligent pair of shutter glasses, in which each optical element is realized using an electro-optical glazing structure of the present invention, fashioned to the dimensions of a shutter glass frame.

Another object of the present invention is to provide an intelligent windshield or viewing screen, which is realized from an electro-optical glazing structure of the present invention.

These and other objects of the present invention will become apparent hereinafter and in the Claims to Invention.

BRIEF DESCRIPTION OF THE DRAWINGS

For a more complete understanding of the Object of the Present Invention, the following Detailed Description of the Illustrative Embodiments of the Present Invention should be read in conjunction with the accompanying Drawings, wherein:

Fig. 1A is a perspective view of a generalized embodiment of the intelligent electro-optical window system of the present invention, wherein the electro-optical glazing structure thereof is electrically switched under microcomputer-control to its totally-scattering state of operation upon detecting a first set of preprogrammed electromagnetic conditions, whereby broad-band electromagnetic radiation (e.g. associated with interior scenery or objects) is completely scattered as the electromagnetic radiation propagates through the electro-optical glazing structure thereof;

Fig. 1B is a perspective view of the generalized embodiment of the intelligent electro-optical window system shown in Fig. 1A, wherein the electro-optical glazing structure thereof is electrically switched under microcomputer-control to its transmission state of operation upon detecting a second set of preprogrammed electromagnetic conditions, where broad-band electromagnetic radiation is transmitted through the electro-optical glazing structure thereof;

Fig. 2 is a cross-sectional view of an illustrative embodiment of the electro-optical glazing structure of the present invention, showing a PSCT liquid crystal material interposed between a pair of

optically-transparent electrically-conductive film layers (e.g. Tin Oxide or optically-transparent photoconductive polymer) supported upon a pair of spaced-part glass substrate panels, the perimeter edges of which are sealed in a conventional manner, and across which a control voltage is applied;

Fig. 3A shows the electro-optical light scattering structure of Fig. 2 operated in its transmission mode, wherein an external voltage is applied across the optically-transparent, electrically-conductive (e.g. Tin Oxide) surfaces (i.e. $V=V_{on}$);

Figs. 3B and 3C show transmission and scattering characteristics for the mode of operation indicated in Fig. 3A;

Fig. 3D shows the electro-optical light scattering structure of Fig. 2 operated in its light scattering mode, wherein no external voltage V is applied across the optically-transparent, electrically-conductive (e.g. Tin Oxide) surfaces (i.e. $V=V_{off}$);

Figs. 3E and 3F show transmission and scattering characteristics for the mode of operation indicated in Fig. 3D;

Fig. 4 is a schematic diagram illustrating the major subsystems and subcomponents associated with the system for manufacturing electro-optical glazing structures in accordance with the principles of the present invention; and

Fig. 5 is a diagram setting forth a flow chart illustrating the steps involved when using the system of Fig. 4 to manufacture low-cost, haze and defect free electro-optical glazing structures hereof in accordance with the principles of the present invention.

DETAILED DESCRIPTION OF THE ILLUSTRATIVE EMBODIMENTS OF THE PRESENT INVENTION

Referring now to the accompanying Drawings, illustrative embodiments of the intelligent electro-optical window of the present

invention will be described in great detail. In each of the figures, like structures and elements shall be indicated by like reference numerals.

In Figs. 1A and 1B, a generalized embodiment of the intelligent electro-optical glazing structure (i.e. window structure) of the present invention is shown installed within an environment (e.g. building or vehicle) having an interior space or volume adjacent the window structure. Typically, the interior space or volume functions as a form of human habitat, although there may be applications in which this is not the case. Preferably, the intelligent electro-optical window structure 1 cooperates with the heating/cooling system 2A of a house, office building, factory or vehicle indicated by reference numeral 2. In such preferred applications, the function of the electro-optical window structure will be to selectively control the flow of electromagnetic radiation through its electro-optical glazing structure and into the interior space, in order to minimize or reduce thermal loading upon the heating/cooling system of the environment.

As shown in Figs. 1A and 1B, the electro-optical glazing structure 1 comprises an electro-optical glazing panel 3 securely supported within a prefabricated window frame 4 which can be realized using virtually any suitable material such as, for example, plastic, metal, rubber, wood or composite material. Within the window frame, a number of system subcomponents are securely mounted, namely: a electromagnetic-radiation sensor 5 for sensing electromagnetic conditions in the outside environment; a rechargeable-type battery 6 for producing electrical power within the window frame; a electromagnetic-powered battery recharger 7 for recharging the rechargeable battery 6; a micro-controller (e.g. RISC-type micro-computer chip with onboard ROM, EPROM and

RAM) 8 for controlling the battery recharger and glazing control signals as required by a radiation flow control program stored within the micro-computer chip; and electrical circuitry 9, response to glazing control signals, for producing control voltages that are applied to the electrically-active elements of the electro-optical glazing structure 3 to electrically switch the same from one optical state to another optical state under microcontroller control.

As shown in Fig. 1A, when a first set of preprogrammed electromagnetic conditions (e.g. a first prespecified band of electromagnetic radiation having power above a first prespecified power threshold) is detected by electromagnetic-radiation sensor, the electro-optical glazing structure 3 is electrically switched to its totally-scattering state of operation under the control of preprogrammed microcontroller 8. In this totally-scattering state of operation, visible and electromagnetic radiation is completely scattered off the glazing structure over a broad band of spectral wavelengths (e.g. from the near IR band, over the optical band, to the far UV band), with about 75% of the incident light being forward scattered and about 25% thereof being back-scattered. In this state of operation, the phase distribution of the wavefront of incident light is sufficiently distorted so as to render the electro-optical glazing structure highly-translucent, but incapable of projecting images therethough without severe distortion, as would be desired in privacy applications.

As shown in Fig. 1B, when a second set of preprogrammed electromagnetic conditions (e.g. a second prespecified band of electromagnetic radiation having power above a second prespecified power threshold) is detected by electromagnetic-radiation sensor, the electro-optical glazing structure 3 is electrically switched to its transmission state of operation under the control of preprogrammed

microcontroller 8. In this transmission state, visible and electromagnetic radiation is transmitted through the electro-optical glazing structure over a broad band of spectral wavelengths (e.g. from the near-IR band, over the optical band, to the far-UV band).

While only two particular scattering/transmission states are illustrated in the above generalized embodiment, it is understood that virtually any set of intermediate scattering/transmission characteristics can be realized by the window structure of the present invention, to provide a "grey-scale" lighting control as required by the particular application at hand. In each such embodiment of the present invention, a particular set of conditions can be predefined to trigger a change in the optical state of the electro-optical glazing structure of the present invention. Then microcontroller is programmed to switch the optical state of the glazing structure upon detecting the corresponding condition. In alternative embodiments, the environmental condition or conditions which cause a switching operation, need not be related to electromagnetic radiation, but may be related to moisture, barometric pressure, temperature, or any other parameter prespecified within the programmed microcontroller 8.

While in theory there exists an infinite number of embodiments of the electro-optical glazing structure of the present invention, one illustrative embodiment of the electro-optical glazing structure will be described in detail below in order to illustrate the inventive features thereof. Various formulations are provided for making the electro-optical glazing structure of the present invention.

By virtue of such ultra broad-band operating characteristics of the electro-optical glazing material hereof, and the novel panel configurations disclosed herein, it is now possible to provide a level

of electromagnetic radiation control hitherto unattainable by prior art smart window systems and methodologies.

<u>The Electro-Optical Glazing Structure Of The Present Invention</u>

Referring to Figs. 2 through 3F, the illustrative embodiment of the electro-optical glazing structure of the present invention will be described in great detail.

As shown in Fig. 2, the electro-optical glazing structure of the illustrative embodiment 3 comprises: a PSCT liquid crystal material 11 interposed between a pair of optically-transparent electrically-conductive film layers 12A and 12B (e.g. Tin Oxide or other optically-transparent photoconductive polymer or like film coating) supported upon a pair of spaced-part glass substrate panels 13A and 13B, respectively, the perimeter edges of which are sealed in a conventional manner, and across which a control voltage 14 is applied under the control of microcontroller 8. Preferably, the sealed electro-optical glazing structure depicted in Fig 2 is mounted within a frame structure as described in connection with the generalized embodiment shown in Figs. 1A and 1B, and incorporates all of the power generation, electromagnetic radiation detection and micro-control mechanisms thereof.

In Fig. 3A, the electro-optical light scattering structure of Fig. 2 is shown operated in its transmission mode or state, wherein an external voltage (e.g. 110 Volts at 50HZ) is applied across surfaces 12A abd 12B (i.e. $V=V_{on}$). In Figs. 3B and 3C, transmission and scattering characteristics for this mode of operation are shown, respectively. In Fig. 3D, the electro-optical light scattering structure of Fig. 2 is shown operated in its light scattering mode or state, wherein no external voltage V is applied across surfaces 12A and 12B (i.e. $V=V_{off}$). In Figs. 3E and 19F, transmission and scattering

characteristics for this mode of operation are shown, respectively. As light is transmitted when an external voltage is applied, and scatters when no voltage is applied, this structure is said to operate in the "normal mode".

Referring now to Figs. 4 and 5, several formulations will now be described for making the electro-optical glazing structure 3 of the present invention using an electrically switchable liquid crystal and polymer blend material which offers significantly lowered manufacturing cost. The material exhibits minimal haze at all viewing angles when in the ON state (i.e. transmission mode). The material is a mixture of non-reactive chiral liquid crystal, a monomer, and small amount of photo-initiator. The advantage is the much lower cost of the monomer material. Unlike all other prior art systems, the present invention utilizes a type of monomer lacking a mesogenic group.

By introducing a polymer network free of mesogenic groups, the coupling between the polymer network and the non-reactive liquid crystal molecules is weaker yet strong enough to stabilize the cholesteric texture in the focal conic state, therefore a modest switching electric field is sufficient to switch all non-reactive liquid crystal molecules along the field direction. The result is a haze free device at all view angles. As an example, one identified monomer from Aldrich is Ethylene Glycol Dimethacrylate (EGD). The monomer is UV polymerizable and has a refractive index of 1.4540 with a chemical structure of $[S_i(CH_3)_2O]_n$. Other UV curable polymers without a mesogenic group have also been identified such as UV10, and UV15-7 from Master Bond (U.S.A.), which can be used for fabricating the PSCT panel. When UV10 and UV15-7 are used to

make the device, no photo initiator is added in the liquid and monomer mixture.

The usage of a smaller molecular weight monomer promotes higher cross-linking site density per unit volume. The higher cross-linking density enhances the mechanical strength of the device.

Most low molecular weight nematic liquid crystals have been found suitable for making the invented PSCT device. Single compound liquid crystal such as the K-, and M-series from EMI (Germany), and multiple compound liquid crystals such as the E-, and ZLI-series from EMI are effective. For example, E7, E44 (both from EMI, Germany), and P9615A (from SLICHEM, China) have been successfully used in making such devices.

Chiral additives are necessary to induce a cholesteric phase in PSCT. A chiral component CB15 has been identified from EMI. It is understood that other chiral additives are also useful in making the PSCT devices.

As mentioned previously, in making large size PSCT devices, the flow streaks of the liquid crystal/polymer mixture creates non-uniformity problems. In order to solve this problem, the addition of small amount of surfactant is helpful for the uniformity as well. The addition of small amount of Poly(Dimethylsiloxane) (viscosity 5cST) shows drastic improvement in panel uniformity. The function of the surfactant is to modify the surface property of the substrates to reduce the differences in the coupling of the substrates to the various components of the liquid crystal mixture. Therefore, all the components in the mixture flow uniformly and maintain their proper ratio in the mixture, eliminating the flow streaks.

A photo initiator is necessary to initiate the polymerization of the polymer compound in the liquid crystal mixture. Several photo

initiators have been identified. They are 2,6-Di-tert-butyl-4-methylphenol (Aldrich), IG500 (Cyba Geigy), Darocur1173 (D1173) (Cyba Geigy). It is understood that other photo initiators are also useful in making the glazing structure of the present invention.

Formulations For Making The PSCT Of The Present Invention

Having identified the preferred ingredients (materials) for making the electro-optical glazing structure of the present invention, it is now appropriate at this juncture to describe in detail several preferred formulations based thereon for making such electro-optical glazing structures.

Example 1:

Ingredient	**Function**	**%**	**Weight (mg)**
Poly(dimethylsiloxane)	surfactant	0.01	0.1032
2,6-Di-tert-butyl-4-methylphenol	photo initiator	0.0029	0.03
P9615A	nematic	89.781	926.3
CB15	chiral	7.1821	74.1
EGD	monomer	3.024	31.2

Example 2:

Ingredient	Function	%	Weight (mg)
Poly(dimethylsiloxane)	surfactant	0.01	0.1021
2,6-Di-tert-butyl-4-methylphenol	photo initiator	0.002	0.02
E44	nematic	91.125	930.5
CB15	chiral	6.4929	66.3
EGD	monomer	2.3699	24.2

Example 3:

Ingredient	Function	%	Weight (mg)
Poly(dimethylsiloxane)	surfactant	0.01	0.10959
IG500	photo initiator	0.1277	1.4
P9615A	nematic	90.09	987.4
CB15	chiral	7.2627	79.6
EGD	monomer	2.5091	27.5

Example 4:

Ingredient	**function**	**%**	**Weight (mg)**
Poly(dimethylsiloxane)	surfactant	0.01	0.1004
Darocur1173 (D1173)	photo initiator	0.2091	2.1
P9615A	nematic	89.694	900.8
CB15	chiral	7.8463	78.8
EGD	monomer	2.2404	22.5

Example 5:

Ingredient	**Function**	**%**
Poly(dimethylsiloxane)	surfactant	0.01
E7	nematic	90
CB15	chiral	7
UV10	monomer	2.99

Example 6

Intgregient	Function	%	Weight (g)
Poly(dimethylsiloxane)	surfactant	0.01	0.0022
D1173	photo initiator	0.05	0.011
P9615A	nematic	90	19.8
CB15	chiral	7.94	1.7468
EGD	monomer	2	0.44

The above liquid crystal and monomer mixtures can be mixed with dichroic dyes to become colored. For example, three dichroic dyes (D5, D35, and D52) have been identified from EMI. The dosage of the dye in the liquid crystal mixture ranges from 0.5% to >5%. The same fabrication method used for the normal PSCT panel (as will be shown in the next section) can be adopted to make the dyed PSCT. The dyed PSCT panel exhibits a colored non-transparent state when no voltage is applied. However, if an electric field is applied, the dye as well as the liquid crystal molecules are all aligned in the field direction to become a lightly tinted transparent state. Using different dyes can yield different colors. The following is a list of the dyed mixtures for the colored PSCT device.

Example 7

Ingredient	Function	%	Weight (g)
Poly(dimethylsiloxane)	surfactant	0.01	0.0022
D1173	photo initiator	0.0498	0.011
P9615A	nematic	89.552	19.8
CB15	chiral	7.9005	1.7468
E.G.D.	monomer	1.99	0.44
D5	dye	0.4975	0.11

Note: The concentration of the dichroic dye D5 can be varied from 0% to 1%.

Example 8

Ingredient	function	%	Weight (g)
Poly(dimethylsiloxane)	surfactant	0.01	0.0022
D1173	photo initiator	0.0498	0.011
P9615A	nematic	89.552	19.8
CB15	chiral	7.9005	1.7468
E.G.D.	monomer	1.99	0.44
D35	dye	0.4975	0.11

Note: The concentration of the dichroic dye D35 can be varied from 0% to1%.

Example 9

Ingredient	Function	%	Weight (g)
Poly(dimethylsiloxane)	surfactant	0.01	0.0022
D1173	photo initiator	0.0499	0.011
P9615A	nematic	89.776	19.8
CB15	chiral	7.9202	1.7468
E.G.D.	monomer	1.995	0.44
D52	dye	0.2494	0.055

Note: The concentration of the dichroic dye D52 can be varied from 0% to 0.5%.

Selecting and Preparing The Substrates For The Electro-Optical Glazing Structure of the Present Invention

In order to make low cost PSCT-based devices in accordance with the present invention, inexpensive glass substrates with an optically clear and electrically conductive layer are preferred. All prior art technologies use special glass substrates that are display standard. Such substrates have an expensive Indium-Tin-Oxide (Tin Oxide) coatings that have high conductivity and high optical transmittance. However, the glass is expensive, making it almost impossible to be used for large size privacy glazing. In order to avoid this shortcoming, equivalent but inexpensive glass must be used. One of the candidates is float glass coated with an inexpensive conductive layer that is optically clear. Such glass has

been identified from one vendor (Pilkington/LOF) and used in making the large size (2'x3') PSCT glazing panels. The glass has a Tin-Oxide conductive coating which is chemical vapor deposited (CVD) with a resistance of 1500 Ohm per square. However, other low cost conductive layers are also suitable for this purpose, such as ZnO_2, silver, or others.

The float glass has a fairly large variation in both thickness and surface flatness; and very possibly has conductive particles generated during the conductive layer coating deposition process. On the other hand, the low cost liquid crystal materials used have a relatively low resistivity. Due to these two major reasons, electric shorting that damages the glazing panel can be a problem. Therefore, an electrically insulating layer is needed on top of the conductive coating on each glass substrate to prevent electric shorts. A thin SiO_x layer will act as the insulating layer. However, in certain cases, if the glass substrates do not have a very large variation in surface flatness and do not have large conductive particles, such an electrically insulating layer is not necessary. However, an optional electric pre-discharge step might be adopted to discard the small size conductive particles. Such a process involves applying an electric voltage (preferably at a value of 4-10V/micron) across an empty glass cell whose gap is determined by the bead spacers applied. For example, floating glass substrates from LOF with a CVD deposited Tin Oxide conductive layer have been successfully used in making the invented large size low cost and uniform PSCT device, even though no insulating coating was introduced.

Description of the System and Method of Manufacture Of the Present Invention

In order to make the large size (2'x3') PSCT panel, the system shown in Fig. 4 and the process depicted in Fig. 5 can be used.

As shown at Block A in Fig. 5, glass reaming apparatus 15 is used to smooth the glass edges to eliminate the possibility of creating glass chips during the manufacturing process.

As shown in Block B in Fig. 5, ultrasonic bathing apparatus 16 is used to help clean the glass surfaces. This is a standard procedure in display industry. In our procedure, the ultrasonic bath solution contains 4 pounds of Alconox detergent from Alconox, Inc. (U.S.A.) in about 80 gallons of water.

As shown in Block C in Fig. 5, rinsing apparatus 17 is used to help wash away the ultrasonic bath detergent from the glass substrates.

As shown in Block D in Fig. 5, optional pre-discharging apparatus 18 can be used to help remove small conductive particles from the substrates. This is a new procedure that is not currently used in the industry. The two substrates are separated by a 30 micron bead spacer. Then a 280V voltage is applied between the two substrates for several minutes. If there are small conductive particles, they will be eliminated by the electric sparking of the high electric field.

As shown in Block E in Fig. 5, liquid crystal mixture apparatus 19 is used to prepare the liquid crystal and polymer mixture according to one of the selected formulations (i.e. recipes) described hereinabove.

As shown in Block F in Fig. 5, liquid crystal coating apparatus 20 is used to apply the liquid crystal and polymer mixture onto the substrate surface. Mechanical spread or knife coating is suitable for this step of the process.

As shown in Block G in Fig. 5, de-gassing apparatus 21 is used to help remove the air bubbles from the coated liquid crystal mixture in a vacuum chamber of a pressure around 10^{-2} Torr.

As shown in Block H in Fig. 5, apparatus 22 is used to place the top glass plate upon and thus cover the liquid crystal mixture, e.g. using mechanical solenoid apparatus mounted inside the vacuum chamber.

As shown in Block I in Fig. 5, after the liquid crystal is fully filled, edge sealing apparatus 23 is used to seal the four edges of the plate assembly using a suitable epoxy.

As shown in Block J in Fig. 5, UV light curing apparatus 24 is usxed to apply UV light (365nm; $3W/m^2$) to the sealed glass plate assembly (e.g. glazing structure) in order to cure the panel for about one hour with the voltage (about 120V) switched on.

Additional Embodiments Of The Electro-Optical Glazing Structure of The Present Invention

The electro-optical glazing panel hereof described hereinabove can be combined in various ways as taught in copending US Application No. 09/032,302, supra, in order to provide intelligent glazing structures capable of controlling light transmission therethrough in any number of radiation bands.

The intelligent glazing structure of the present invention taught hereinabove allows a very large part of the visible spectrum to be substantially totally scattered.

Having described such alternative embodiments of the present invention, further modifications thereto readily come to mind.

For example, the electro-optical glazing structures described above can be stacked and laminated together, in virtually any number or ordering, so as form composite electro-optical glazing structures having more than two optical states (e.g. four or more). Such electro-optical glazing structures can be used to construct sophisticated window systems capable of providing complex levels of solar and/or visible radiation control.

Electrically controlled CLC-based smart windows of the present invention can be used in homes, schools, offices, factories, as well as in automobiles and airplanes to provide privacy, brightness control, and reduce thermal loading on heating and cooling systems employed therein.

The electro-optical glazings of the present invention can be used to make intelligent sunglasses and sun visors for use in a variety of applications. In such embodiments of the present invention, the electro-optical glazing of the present invention is realized in the form of a pair of lenses which are mounted within a frame supportable upon the head of its user, as in conventional eyeglasses or sun-visors. The programmed microcontroller, battery, electromagnetic detector, battery recharging circuitry and optical state switching circuitry embodied within the window frame shown in Figs. 1A and 1B can be reduced in size and embodied within the ultra-compact sunglasses frame of this illustrative embodiment of the present invention.

The electro-optical glazings of the present invention can be used in automotive vehicles, maritime vessels, aircrafts and spacecrafts. The structures of the present invention can also be used to make

spatial light intensity modulation (SLM) panels, having pixelated or unpixelated surfaces.

The transmission and scattering characteristics of the electro-optical panels of the present invention are bi-directional in nature, and do not depend on the polarization state of the wavelengths of incident light. Thus regadless of the polarization state of incident light, when the electro-optical glazing panel is operated in its transmission mode, incident light is transmitted in either direction with minimal scattering; whereas, when the electro-optical glazing panel is operated in its scattering mode, incident light is scattered in either direction, wherein the ratio of forward-scatter-to-backward-scatter being at least 3/1 (e.g. 75%/25%). It is understood, however, that this ratio can be modified from embodiment to embodiment of the present invention as the application at hand requires.

The modifications described above are merely exemplary. It is understood that other modifications to the illustrative embodiments will readily occur to persons with ordinary skill in the art. All such modifications and variations are deemed to be within the scope and spirit of the present invention as defined by the accompanying Claims to Invention.